The Growth of Jack Pine and Black Spruce Seedlings in Heavy Metal Contaminated Soils Collected Near the Inco Smelter at Thompson, Manitoba

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THE GROWTH OF JACK PINE AND BLACK SPRUCE SEEDLINGS IN HEAVY METAL CONTAMINATED SOILS COLLECTED NEAR THE INCO SMELTER AT THOMPSON, MANITOBA.

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ABSTRACT

The growth response of jack pine (Pinus banksiana Lamb.) seedlings and black spruce (Picea mariana (Mill.) BSP) seedlings reared in heavy metal contaminated surface organic soils (LFH) collected from sites near the Inco Metals Company smelter at Thompson, Manitoba was investigated. Differences in physical development of seedlings were observed between sites over a twenty-four week greenhouse growing period. It appears that toxic levels of metals, especially nickel and copper, are being absorbed by the seedling root tissue. Significant growth inhibition of seedling roots is occurring at sites within a 5 km radius of the smelter. There is concern that metal concentrations in the LFH medium may be contributing to a decline in the ability of these species to regenerate successfully. The results of this study remain to be field tested.

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1. INTRODUCTION

The Inco Metals Company located at Thompson, Manitoba operates an integrated nickel mining, milling, smelting and refining complex. Smelting operations began in 1961. Of primary environmental concern are the stack emissions of sulphur dioxide and flue dust. The flue dust or particulate is comprised, in part, of heavy metals.

A joint Federal/Provincial forest study with the Northern Forest Research Centre, Canadian Forestry Service and the Environmental Management Division commenced in April, 1977. The overall objective of the joint study was to determine the environmental impact of airborne sulphur dioxide and heavy metal particulates, emitted from mining smelters in northern Manitoba, on the local forest ecosystem. Initial results showed a gradient of heavy metal accumulation in the soils surrounding the smelter (Wotton and Hogan 1981). The specific objective of this follow-up study was to investigate, in a greenhouse environment, the growth response of jack pine (Pinus banksiana Lamb.) and black spruce (Picea mariana (Mill.) BSP) seedlings reared in LFH (surface organic soils) of various heavy metal loads. LFH is defined, according to the Soil Classification System for Canada, as organic layers where in L the original structures are easily discernable, in F the accumulated partly decomposed organic structures are difficult to recognize and in H the original structures are indiscernable (Canada Agriculture 1974).

It has been well documented that the physiological development of plants can be significantly inhibited by the uptake of heavy metals (Hutchinson and Whitby 1973, Whitby and Hutchinson 1974, Mitchell and Fretz 1977, Russo and Brennan 1979, Fessenden and Sutherland 1979, Malhotra and Khan 1981, Lozano and Morrison 1982).

Jack pine and black spruce are the major coniferous tree species of the boreal forest ecosystem in the Thompson area (Kotowycz et al. 1974). The ability of these species to maintain themselves as productive components of the ecosystem is essential to the integrity of the local forest and is of concern to the Province of Manitoba.

In response to this concern the Environmental Management Division initiated this investigation to determine the effects of heavy metals in forest soils on the growth and development of tree seedlings. This report presents results of this study.

2. METHODS

2.1 Soil/Seed Preparation

LFH collections were made in June, 1981 for jack pine and June, 1982 for black spruce from each of the twelve study site locations established by the joint Federal/Provincial study group (Appendix 1). At the same time, cones were collected from five randomly selected trees for each species at site 9, the control site. The LFH material from each site was air dried and ground to a uniform texture for standardization among sites and to facilitate container loading and moisture maintenance of the medium. Seed was extracted from the cones, cleaned and an equal quantity of seed from each tree was bulked.

The uniform textured LFH for each site was loaded into three "styrobloc 20" styro containers (each container has 45 holes with a volume of 315 cc per hole). The containers were seeded at a rate of three to five seeds per hole, top dressed, treated with an anti-fungal preparation and thoroughly moistened. The seeded styroblocs were placed on floor level greenhouse benches. Following germination and thinning to one seedling per hole, the seedlings were maintained for a period of twenty-four weeks, September 2, 1981 to February 17, 1982 for jack pine and November 16, 1982 to May 24, 1983 for black spruce.

2.2 Growth Environment

Greenhouse facilities for the growth study were located at the University of Manitoba. Temperatures throughout the study were maintained between 20°C and 25°C. Relative humidity was maintained between 40% and 60%. Supplementary lighting was provided at 100 cm above the benches for 18 hours each day beginning at 0600 hours and continuing till 2400 hours. Adequate ventilation, weeding and insect control were also provided. Every second day, the seedlings were watered using a mist nozzle at a rate of 4 litres per minute for approximately one minute per tray.

2.3 Seedling/Soil Measurement/Analyses

All seedling growth measurements were taken immediately following the termination date for each study. Following extraction of the entire seedling from each hole, shoot length above the root collar and root length were recorded. The seedlings from each styrobloc for each site were separated into roots and shoots; mean oven dry mass was determined for each site.

Plant tissue and a pre-study sample of LFH from each study site were submitted to the W. M. Ward Technical Services Laboratory for analyses of total lead, zinc, iron, cadmium, copper and nickel by atomic absorption spectrophotometry.

3. RESULTS AND DISCUSSION

3.1 Metals in Organic Soils

Metal concentrations in the LFH growing medium for each species are presented in Table 1. It is apparent that the sites closest to the Inco smelter have the highest levels in the surface organic soil layer. Figure 1 for jack pine and Figure 2 for black spruce illustrate graphically the trend of decreasing Ni and Cu levels in the LFH with increasing distance from the smelter. Significant correlations were found for metal levels in the LFH versus distance from the Inco stack, especially for Ni and Cu (Appendix 2).

In the jack pine study nickel concentrations in LFH at sites within a 5 km radius of the Inco stack were up to seventy five times the levels found at site 9, the control. For example, at site 11 the Ni level in the LFH was 2173 µg/g compared with 29 µg/g at site 9 (Table 1). For the black spruce study the concentration of Ni in LFH for sites 9 and 10 was similar in magnitude to the jack pine study (24 µg/g at site 9 and 1813 µg/g at site 10).

A recent study of metal accumulation in soils near the Inco smelter observed levels of Ni and Cu with the same magnitude and deposition pattern as in this study (Phillips and Slaney 1981). Wotton and Hogan (1981) also found high levels of Ni and Cu in the surface organic soils within a 5 km radius of the Inco smelter.

Earlier studies also indicated that the binding capacity of the surface organic layer had not been exceeded since metal levels in the underlying mineral soil are not yet elevated. This suggests that there is potential for further accumulation of metals in the LFH.

3.2 Metals in Seedling Tissue

The levels of metals found in seedling tissue for each species are presented in Tables 2 and 3. Graphs of Ni and Cu levels in seedling tissue versus distance from the Inco smelter are presented in Figures 3 and 4 for jack pine and black spruce respectively. Significant correlations were found for metal levels in seedling tissue versus distance from the stack for each species (Appendix 4).

Significant correlations also exist for metal levels in the LFH versus the metal levels found in seedling tissue for each species (Appendix 3). This relationship is most apparent in seedling roots where high concentrations of Ni and Cu were found (Tables 2 and 3 and Figures 5 and 6). In the jack pine study Ni concentrations in root tissue at sites within a 5 km radius of the Inco stack, were up to fifty-six times the level found at control site 9, that is, 1577 µg/g at site 10 and 28 µg/g at site 9. For the black spruce study the level of Ni in seedling tissue was not as high (Table 3) however, the magnitude of difference between the control site 9 and site 10 was thirty-six times (14 µg/g for site 9 versus 511 µg/g for site 10).

The seedling roots were not washed during preparation for analyses. However, an attempt was made to manually remove as much of the dry soil material as possible. It is conceded that soil particles still attached to rootlets and root hairs must contribute in part to the high levels of metals found in root tissue. However, we believe that a substantial amount of the metals were actually incorporated in the root tissue since uptake to the shoots is confirmed (Tables 2

and 3). In any case a gradient of decreasing metal in root tissue with increasing distance from the smelter exists (Figures 3 and 4) and is substantiated by the strong correlations which were found (Appendix 4).

3.3 Seedling Growth

Data on seedling growth and biomass for each species are presented in Table 4. Seedling growth, especially root length at sites 10 and 11, was clearly suppressed. Even sites 4 and 5, located 11 km south and 9 km southeast of the smelter respectively, exhibited growth inhibition although not as pronounced as sites within a 5 km radius of the stack. Significant correlations exist for seedling growth versus distance from the smelter for each species (Appendix 4). A graph of jack pine root growth versus distance from the smelter is presented in Figure 7. The correlation coefficient (r^2) for black spruce root growth versus distance from the smelter was lower but nevertheless highly significant. It is thought that the low average black spruce growth at site 7 accounted for the poorer relationship compared with that for jack pine. If the root growth value for site 7 is omitted the correlation is improved substantially ($r^2 = 0.61$). It is not known whether the black spruce growth suppression at site 7 was species specific or if an unknown variable during the rearing of the seedlings affected the growth. However a strong inverse relationship for Ni and Cu in LFH versus black spruce root growth does exist (Figure 8).

Significant correlations for each species were found for seedling growth and biomass versus metal levels in seedling tissue

(Appendix 4). Figures 9 and 10 demonstrate the inverse relationships between root growth and Ni and Cu in root tissue in jack pine and black spruce respectively. Root growth was highly correlated with all metals except cadmium and zinc in jack pine root tissue and with all metals except iron for black spruce root tissue.

The data show that those sites closest to the smelter have the highest concentrations of metals in the LFH and seedling tissue, and exhibit the greatest degree of seedling growth inhibition. Growth inhibition was greatest in the roots. Root elongation was virtually non-existent and in some cases limited only to the formation of rudimentary buds. Roots had very little lateral development, few or no root hairs and in some cases appeared blackened. This is typical of metal toxicity symptoms observed in other growth studies (Hutchinson and Whitby 1973 and 1977, Whitby and Hutchinson 1974, Malhotra and Blauel 1980). The photographs in Figure 11 demonstrate the degree of growth suppression found in this study.

Winterhalder (1981) suggested that one explanation for the root growth interference phenomenon was competition for binding sites at the root surfaces. However, Hutchinson and Whitby (1973), in a study of metal content of seedlings grown in soil-water extracts, confirmed that uptake of Cu and Ni into root tissue did occur. In a follow-up study they found high concentrations of metals in carefully washed root material (Whitby and Hutchinson 1974). This suggests that the heavy metal toxicity they observed may have been caused by factors other than root surface interference. Malhotra and Khan (1981), in a study of heavy metal effects on enzymes of jack pine seedlings, found

that severe inhibition of enzyme activity was related to metal concentrations in needle and root tissue. This suggests that growth inhibition may be related to interference of plant metabolic processes. Ernst et al. (1983) showed that changes in plant enzymatic activity or metabolic disturbances such as chlorosis, necrosis and dwarfism were caused by stress, such as heavy metal toxicity. In the present study these same physical changes were consistently observed in the seedlings grown in LFH from sites within 5 km of the Inco smelter. It is believed that two major factors may have been responsible for this seedling growth inhibition; elevated heavy metal levels in the LFH causing ion exchange competition at the root surfaces and/or elevated metal levels in seedling tissue causing direct or indirect toxic effects. It is not known if these growth inhibition effects would persist if the seedlings were able to successfully establish their root systems in the underlying mineral soil.

The data indicate that seedling growth is affected by high concentrations of heavy metals especially Ni and Cu in surface organic soils. These two elements, with iron (Fe) are the major metal emissions from the Inco operation. Furthermore, it is evident that the present levels of metals found at sites within a 5 km radius of the smelter already severely inhibit seedling growth. Further experimentation in the field to observe the long-term response to elevated soil metal levels is needed in order to better assess the present and future integrity of the conifer forest ecosystem in the Thompson area.

4. CONCLUSIONS

1. A highly significant inverse relationship exists between heavy metal levels in the LFH (surface organic soil layer) and distance from the Inco smelter.
2. Present levels of heavy metals found in the LFH within a 5 km radius of the smelter are severely inhibiting the growth of conifer seedlings.
3. The heavy metals Ni and Cu appear to be concentrating in the root tissue of the seedlings and severely inhibiting root development.
4. There is a concern that the capability of jack pine and black spruce to regenerate will be substantially reduced over a greater radius from the smelter if metal emissions continue to disperse and accumulate at their current level.

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TABLE 1: Mean metal concentration in LFH by study site.

Study Site	Distance (km)	Metal Concentration (µg/g)											
		Cu		Ni		Pb		Zn		Fe		Cd	
		JP	BS	JP	BS	JP[1]	BS[2]	JP	BS	JP	BS	JP	BS
1	4.0	165	151	822	551	28	35	58	58	8110	10015	0.8	0.8
2	12.2	27	53	253	372	17	28	60	54	8110	6627	0.5	0.5
3	31.8	12	23	79	114	16	26	41	57	3990	4531	0.5	0.6
4	11.0	49	61	399	451	17	23	61	64	6550	5302	0.7	1.0
5	9.0	54	77	370	490	14	21	45	35	3680	7072	0.6	0.6
6	15.7	36	48	270	288	17	17	51	57	8730	4097	0.6	0.6
7	21.8	20	48	117	197	14	18	58	57	4300	3796	0.6	0.5
9	66.0	7	9	29	24	14	17	33	35	5110	4441	0.3	0.4
10	2.3	550	925	1821	1813	24	33	73	50	13720	16173	0.8	0.9
11	1.5	1210	1057	2173	1456	20	30	52	50	14960	15176	1.2	0.8
12	4.3	204	292	1233	1107	42	31	87	61	17450	16303	0.8	0.8
13	18.0	12	16	47	57	55	18	76	50	3300	3873	0.6	0.7

1. jack pine
2. black spruce

TABLE 2: Mean metal concentration in jack pine seedling tissue by study site

Study Site	Distance (km)	Metal Concentration in Jack Pine Seedling Tissue (µg/g)											
		Cu		Ni		Pb		Zn		Fe		Cd	
		Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots
1	4.0	64	22	550	64	11.2	1.9	167	76	2267	53	2.5	0.9
2	12.2	29	29	280	51	5.3	1.5	153	84	239	46	2.9	0.9
3	31.8	16	20	68	23	3.6	1.3	117	108	603	47	1.5	0.7
4	11.0	44	21	690	79	6.3	1.6	230	64	2133	74	2.5	0.7
5	9.0	49	24	837	79	5.3	1.2	239	57	1818	64	2.6	0.5
6	15.7	53	31	351	47	6.3	1.7	174	81	2245	80	1.5	0.4
7	21.8	23	28	141	39	4.8	1.8	190	122	1623	87	2.2	0.7
9	66.0	23	32	28	11	5.8	1.9	152	134	1025	104	1.2	0.5
10	2.3	346	30	1577	88	18.4	10.8	164	32	9839	148	2.8	0.8
11	1.5	306	28	1484	140	10.7	4.8	104	41	4484	92	2.1	0.6
12	4.3	80	21	1267	89	9.8	2.0	292	47	4649	134	3.6	0.6
13	18.0	26	30	22	7	12.5	2.6	556	159	879	77	2.2	1.3

TABLE 3: Mean metal concentration in black spruce seedling tissue by study site

Study Site	Distance (km)	Metal Concentration in Black Spruce Seedling Tissue (µg/g)											
		Cu		Ni		Pb		Zn		Fe		Cd	
		Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots
1	4.0	45	8	156	17	3.3	0.7	86	58	1638	248	0.6	0.1
2	12.2	27	7	94	25	6.5	1.1	80	40	1627	41	1.1	0.2
3	31.8	18	8	41	7	6.4	0.9	89	58	1329	38	0.9	<0.1
4	11.0	40	11	234	24	7.3	1.2	93	38	1959	33	1.4	<0.1
5	9.0	53	13	288	28	6.0	1.2	80	33	2093	42	1.3	0.1
6	15.7	34	13	162	19	5.1	0.7	87	41	1246	44	1.3	0.2
7	21.8	28	31	65	32	7.3	2.4	67	109	794	99	0.5	0.3
9	66.0	16	10	14	4	6.3	1.6	80	60	1226	56	1.3	0.5
10	2.3	279	29	511	37	11.0	5.8	22	42	2084	79	<0.1	<0.1
11	1.5	212	18	259	23	6.9	6.0	94	33	1363	54	<0.1	<0.1
12	4.3	67	20	317	54	5.7	4.9	50	31	1994	55	0.5	0.2
13	18.0	17	10	17	4	5.8	2.0	66	49	968	48	1.0	0.2

TABLE 4: Mean seedling growth and biomass measurements by study site.

Study Site	Distance (km)	Oven Dry Shoot Mass (g)		Oven Dry Root Mass (g)		Shoot Length (cm)		Root Length (cm)	
		JP[1]	BS[2]	JP	BS	JP	BS	JP	BS
1	4.0	0.2	0.2	0.1	0.03	4.9	8.5	20.1	17.9
2	12.2	1.4	1.5	0.5	0.4	8.2	19.9	27.9	20.4
3	31.8	0.9	0.7	0.5	0.2	6.8	13.7	30.8	19.1
4	11.0	0.3	0.4	0.1	0.1	5.0	9.6	20.4	15.1
5	9.0	0.3	0.4	0.1	0.1	4.8	9.0	20.3	14.9
6	15.7	0.6	0.5	0.2	0.1	5.4	10.9	23.8	16.2
7	21.8	0.7	0.1	0.2	0.01	6.3	4.9	24.6	8.9
9	66.0	0.5	0.7	0.2	0.2	6.6	11.0	28.1	19.8
10	2.3	0.1	0.01	0.03	0.003	3.3	2.3	4.9	2.2
11	1.5	0.1	0.4	0.1	0.01	5.2	4.3	14.1	5.3
12	4.3	0.5	0.04	0.2	0.01	5.6	3.3	22.9	4.1
13	18.0	1.1	1.2	0.5	0.4	6.5	17.6	2.9	23.3

1. jack pine
2. black spruce

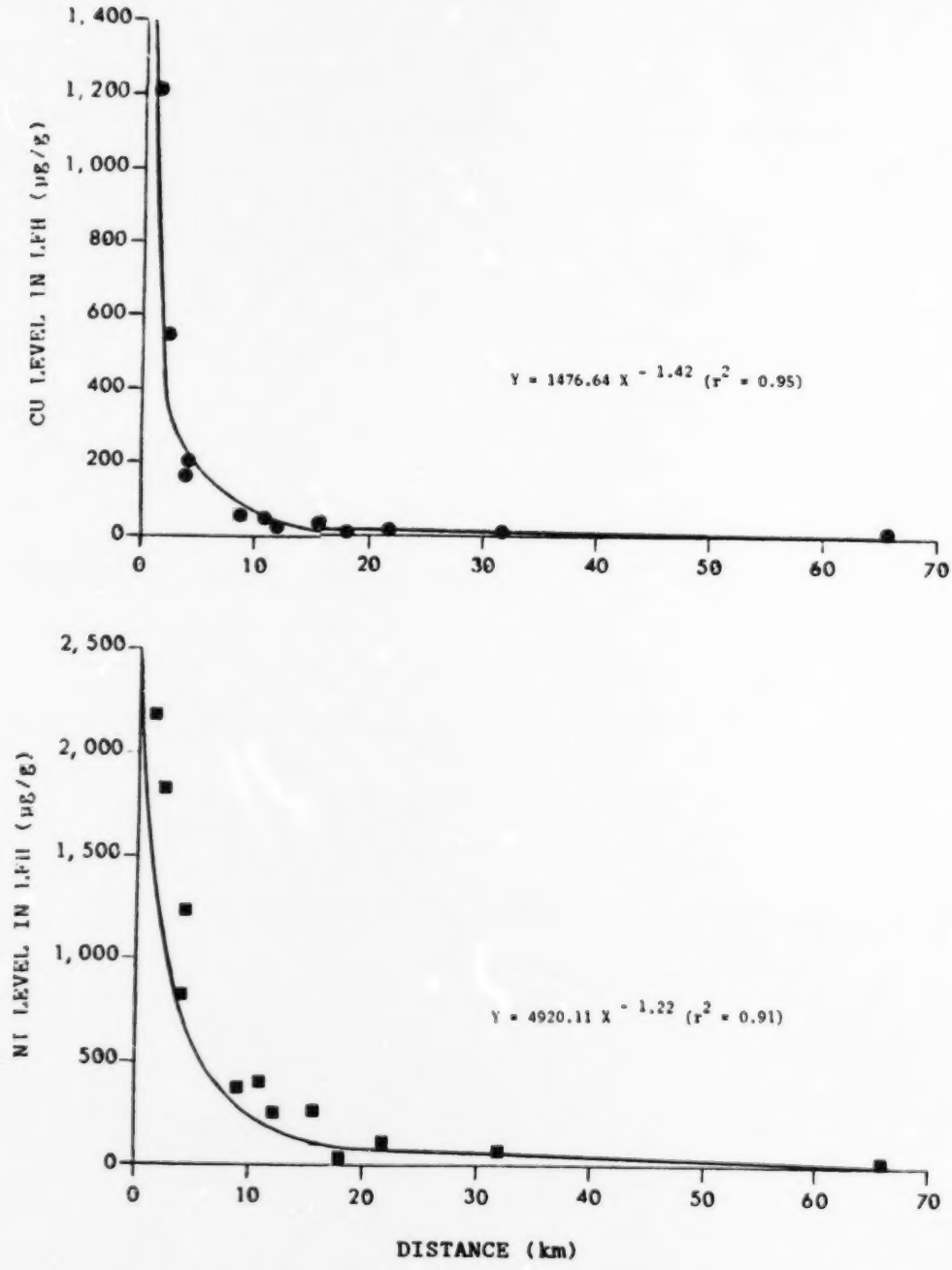


Figure 1: Graph of Cu and Ni levels in LFH versus distance from the Inco Smelter for jack pine.

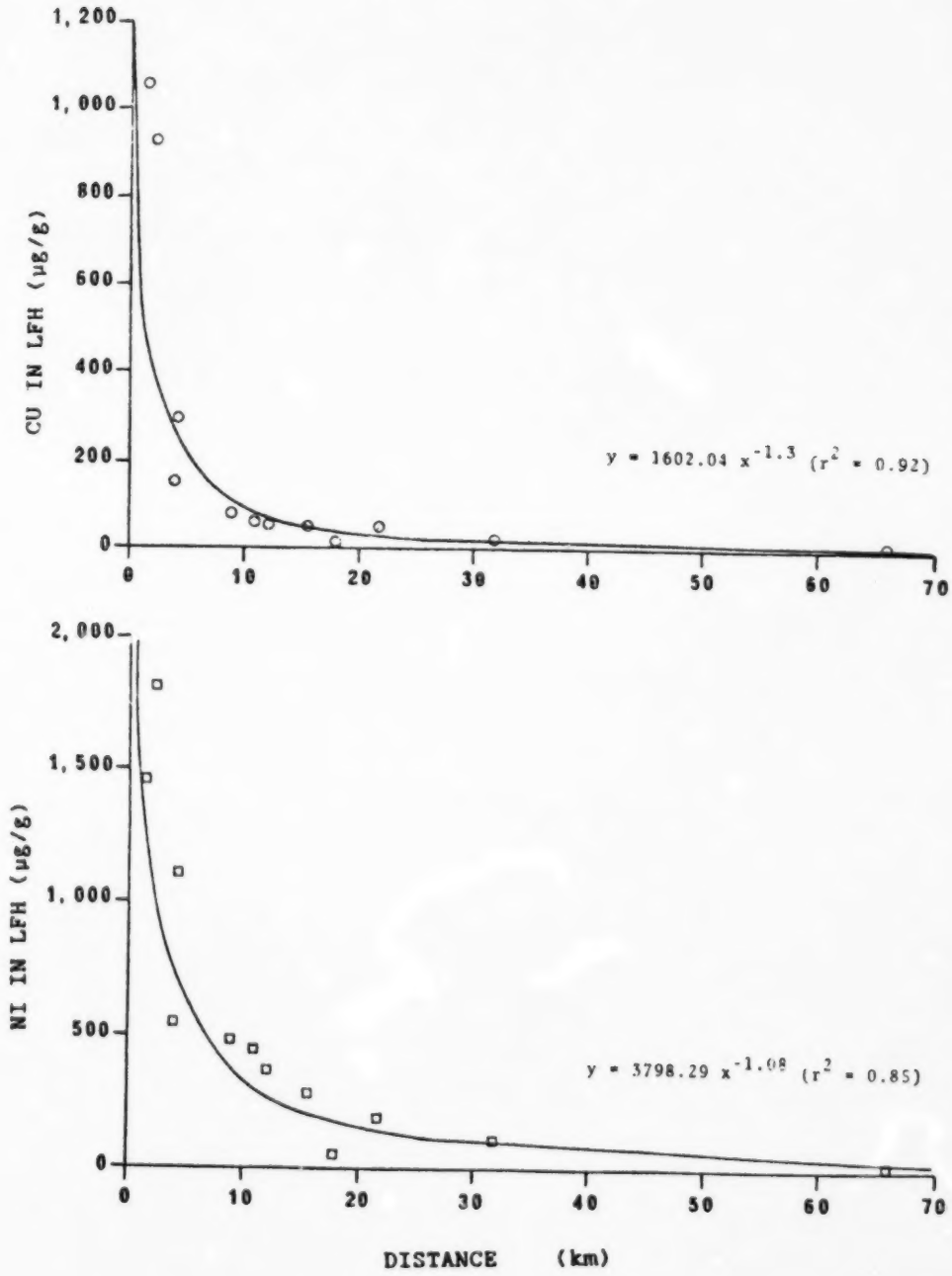


Figure 2: Graph of Cu and Ni levels in LFH versus distance from the Inco Smelter for black spruce.

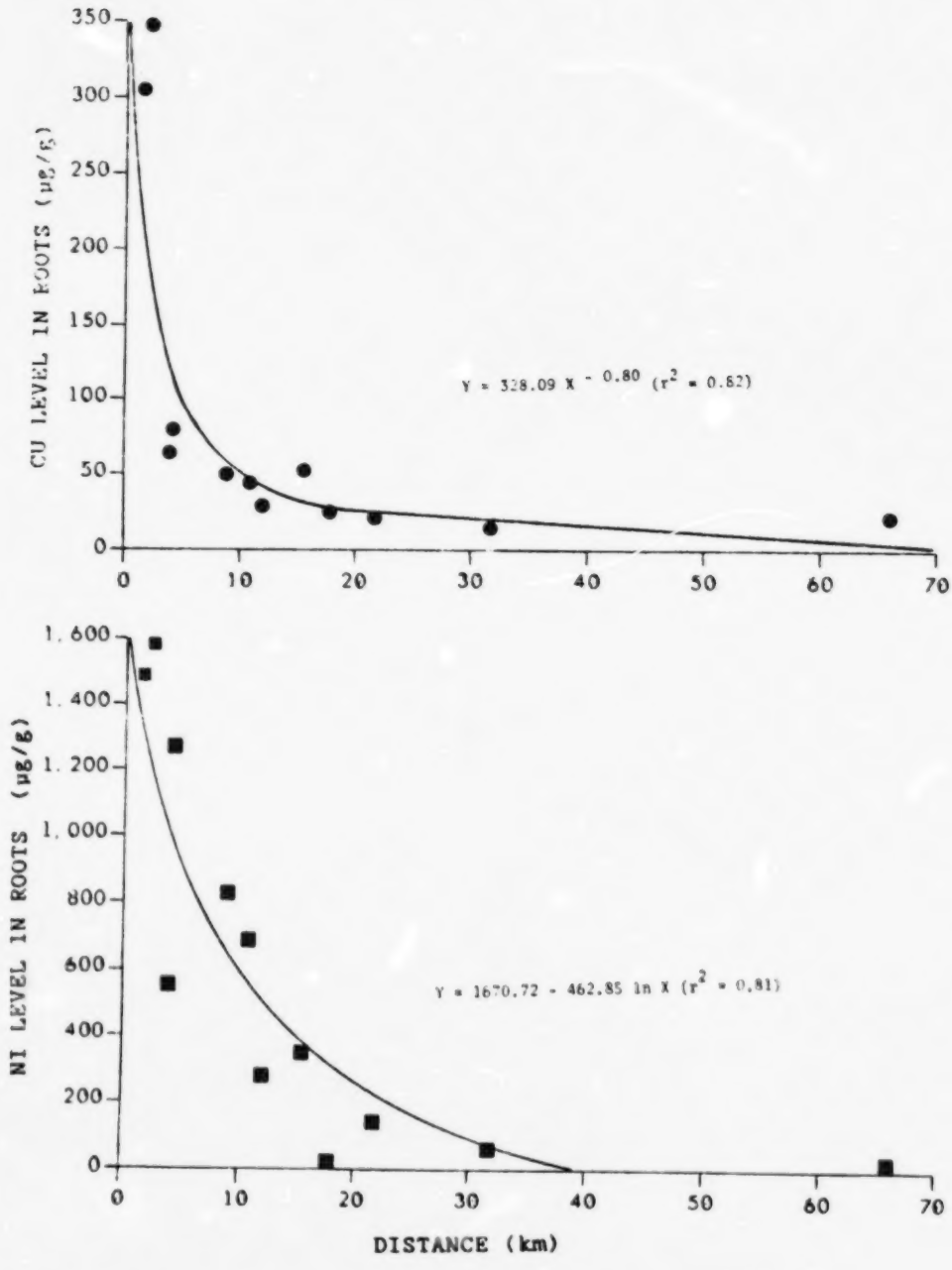


Figure 3: Graph of Cu and Ni levels in seedling root tissue versus distance from the Inco Smelter for jack pine.

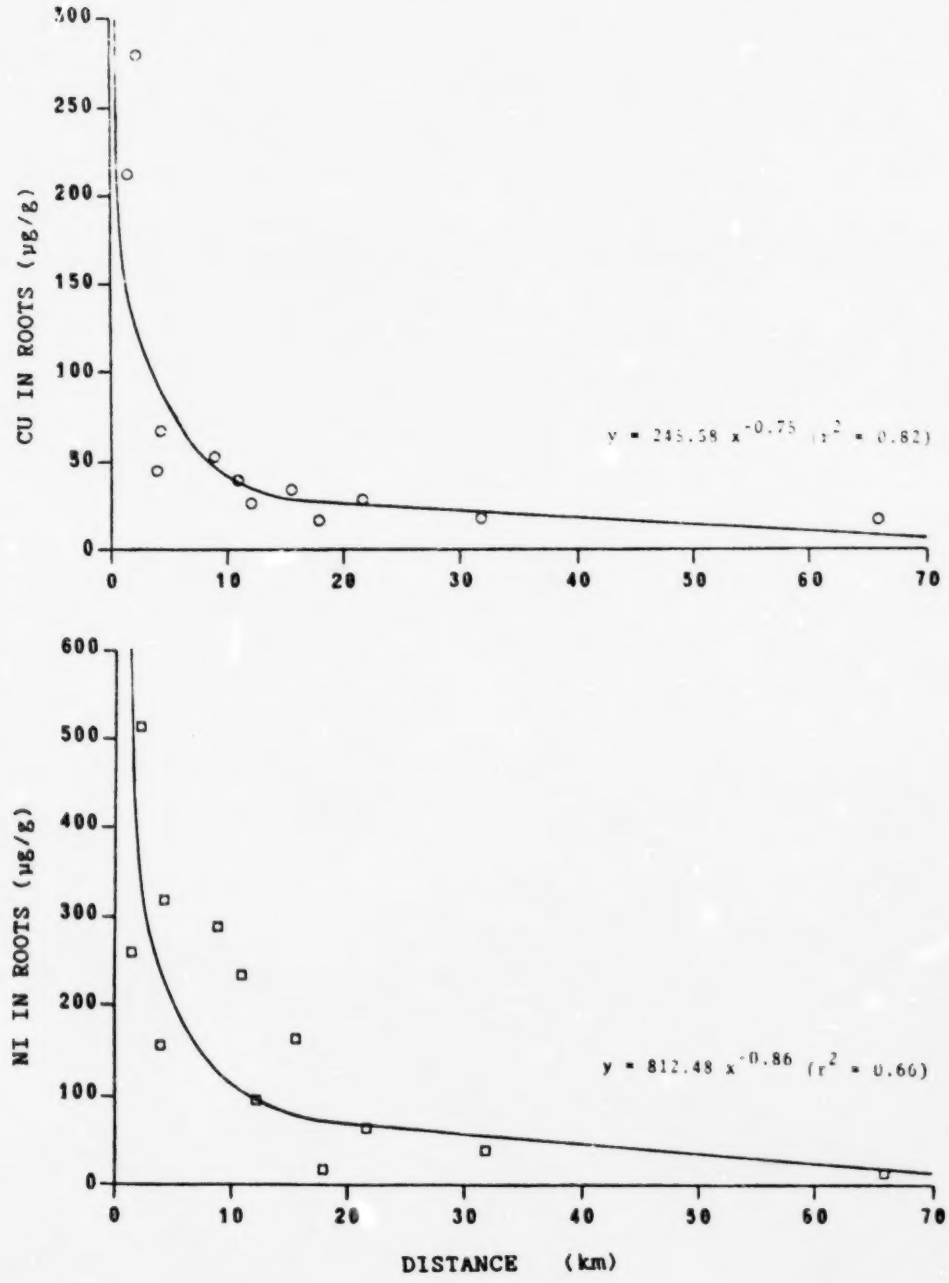


Figure 4: Graph of Cu and Ni levels in seedling root tissue versus distance from the Inco Smelter for black spruce.

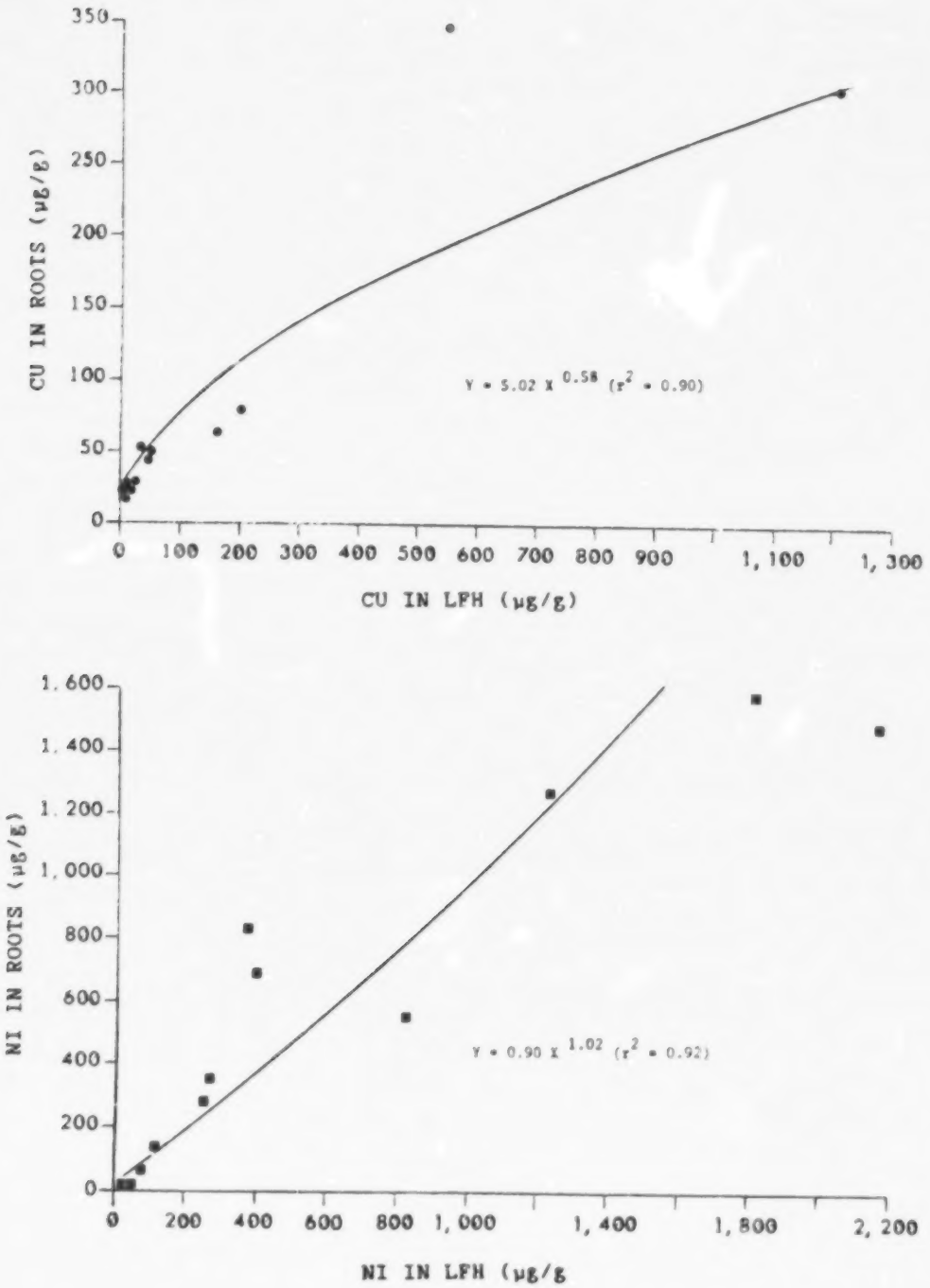
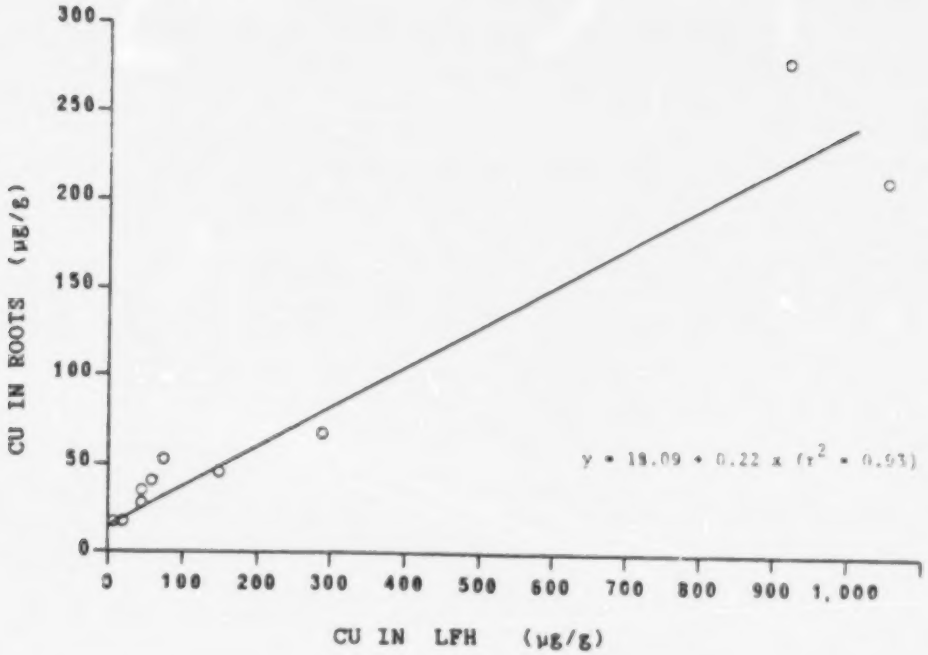


Figure 5: Graph of Cu and Ni levels in LFH versus Ni and Cu levels in seedling root tissue for jack pine.



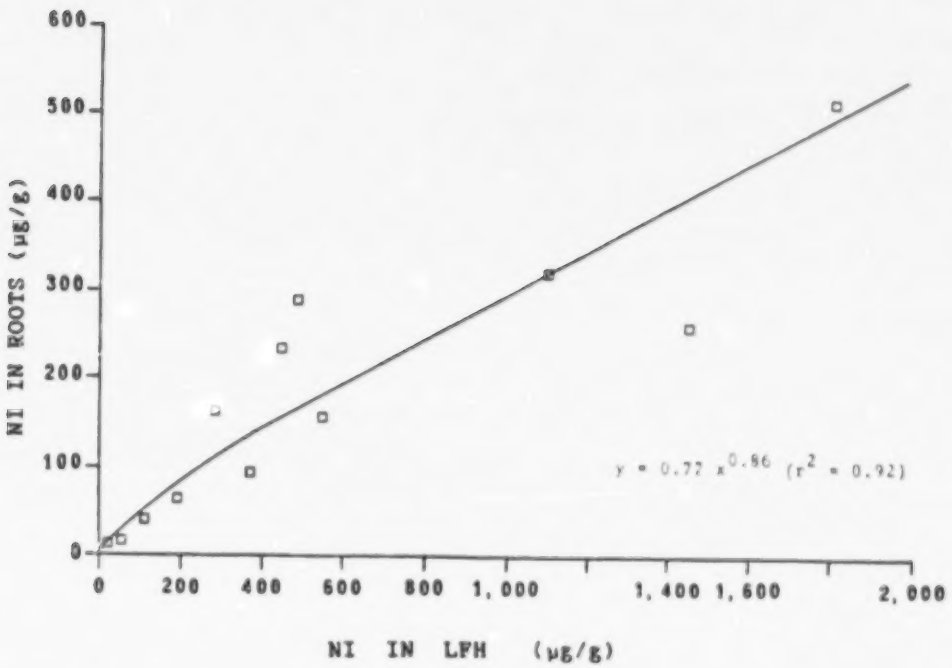


Figure 6: Graph of Cu and Ni levels in LFH versus Ni and Cu levels in seedling root tissue for jack pine.

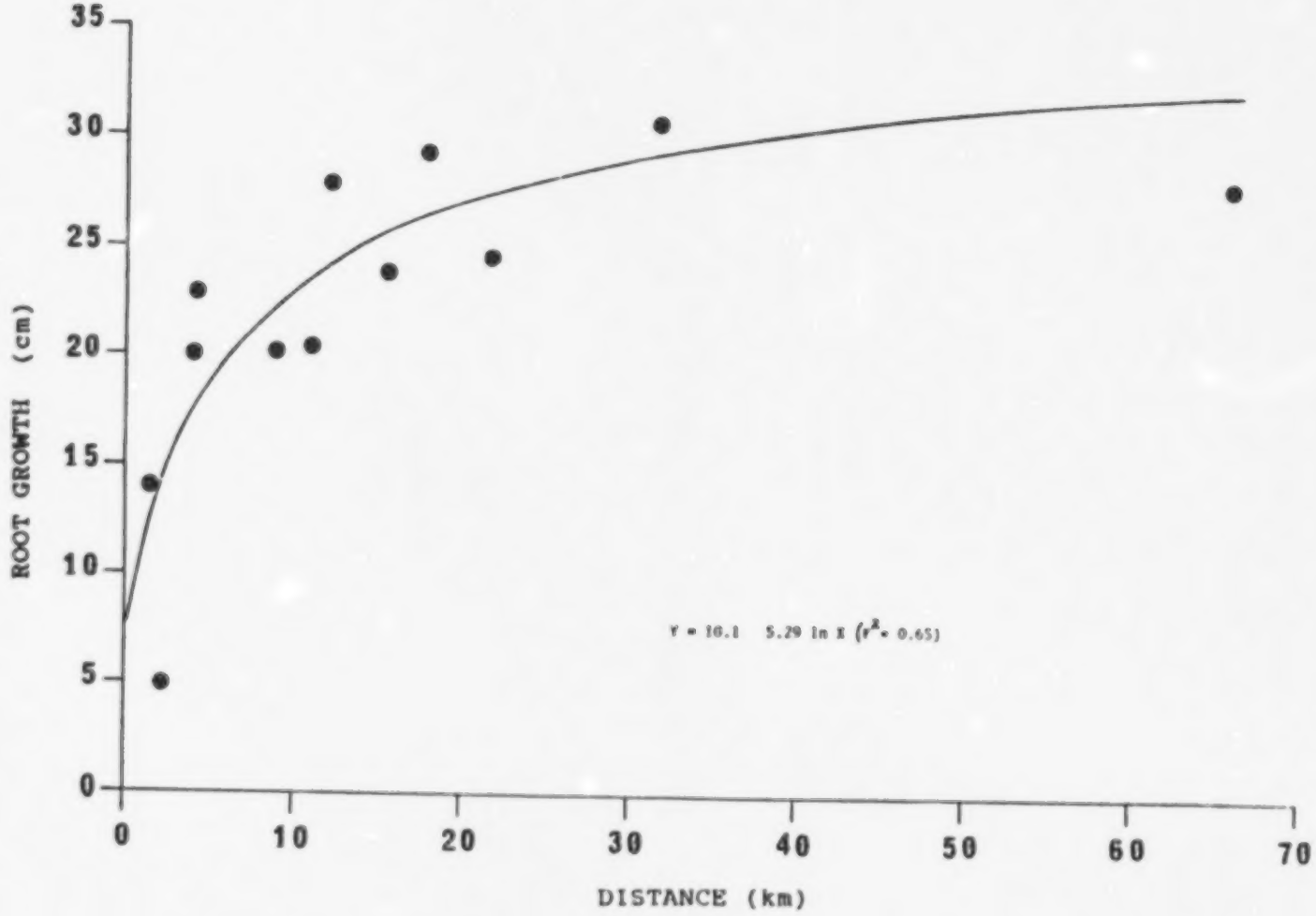
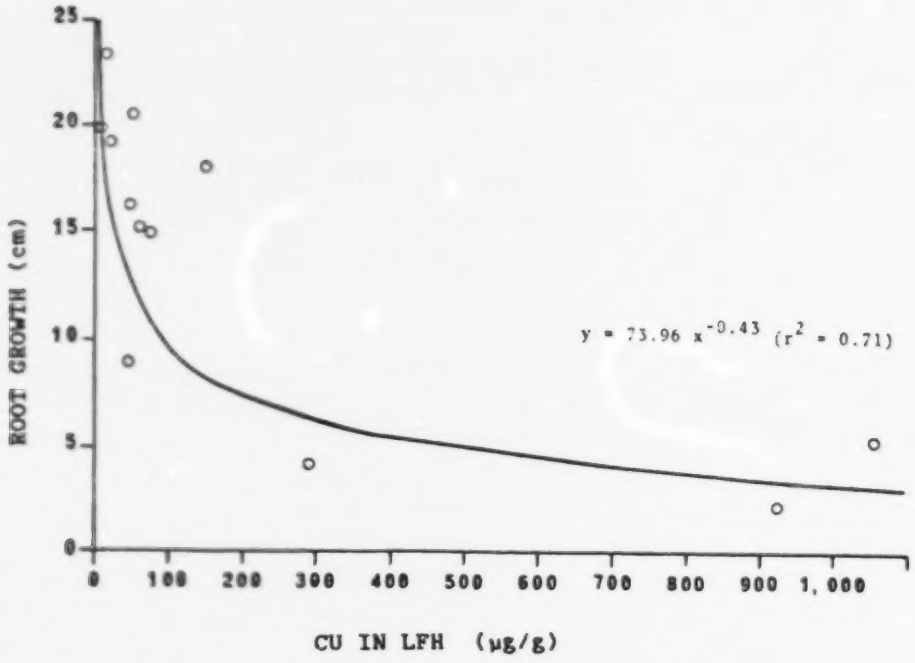


Figure 7: Graph of seedling root growth versus distance from the Inco Smelter for jack pine.



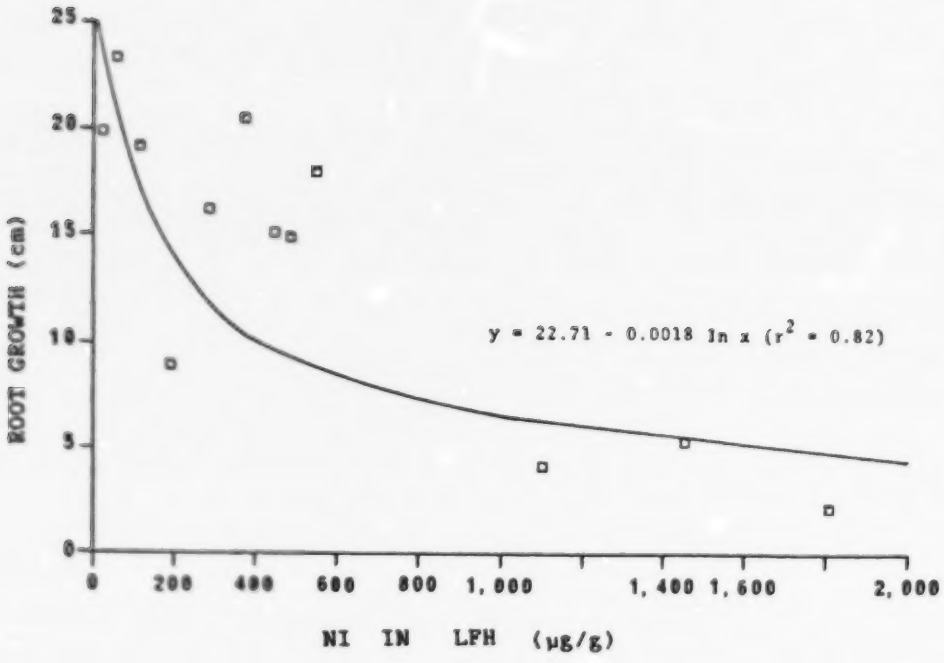


Figure 8: Graph of Cu and Ni in LFH versus root growth for black spruce.

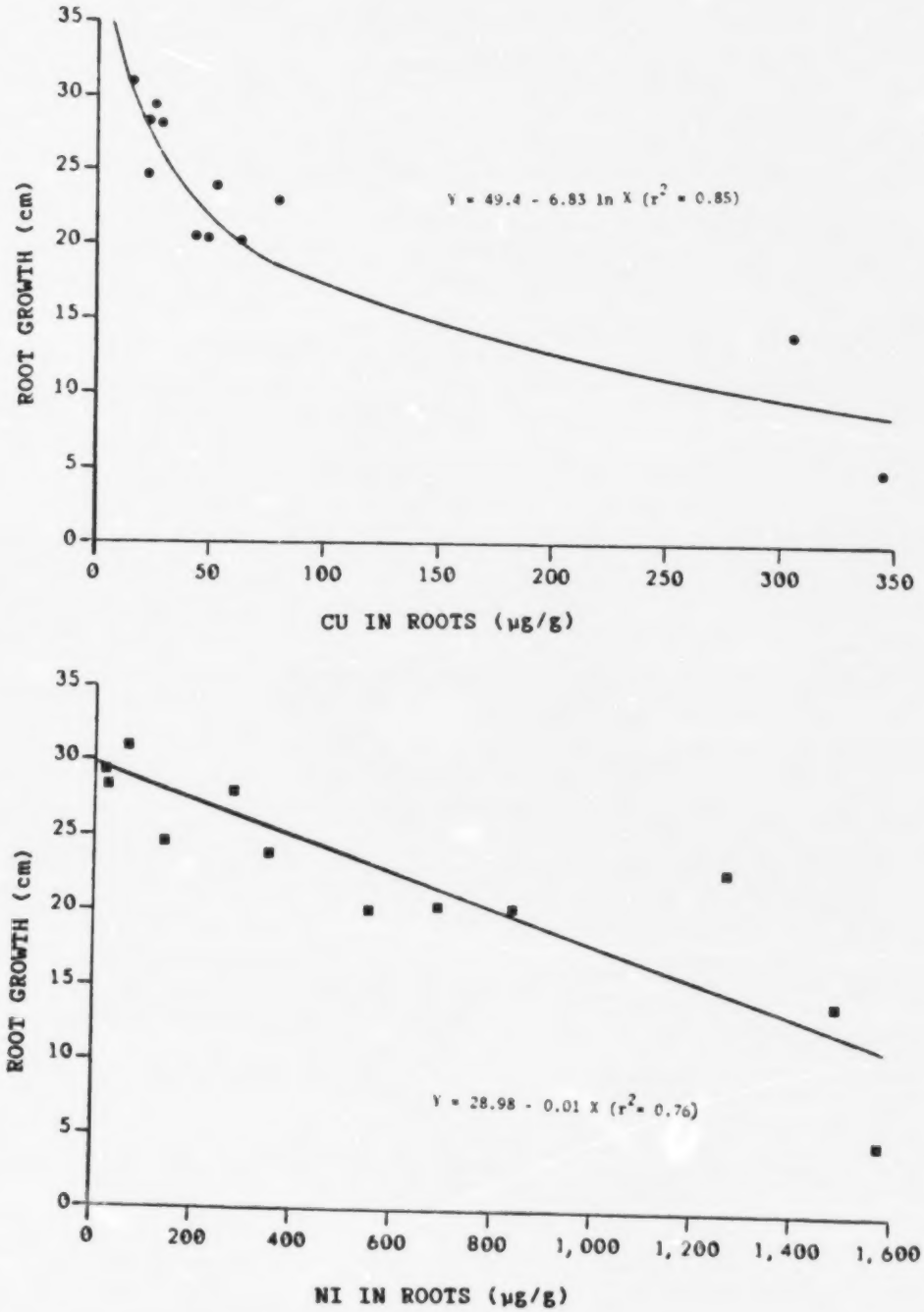


Figure 9: Graph of Cu and Ni in seedling root tissue versus root growth for jack pine.

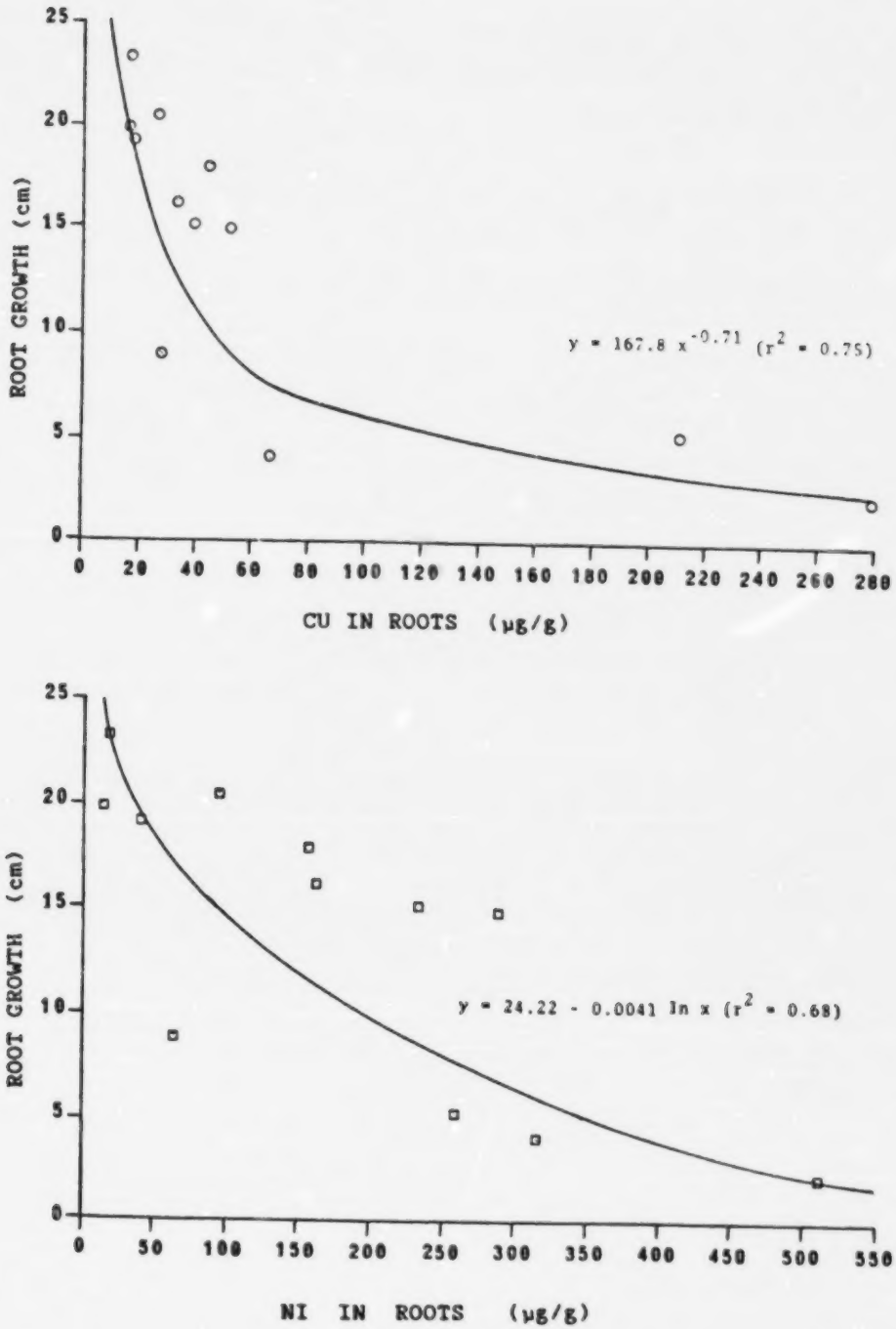
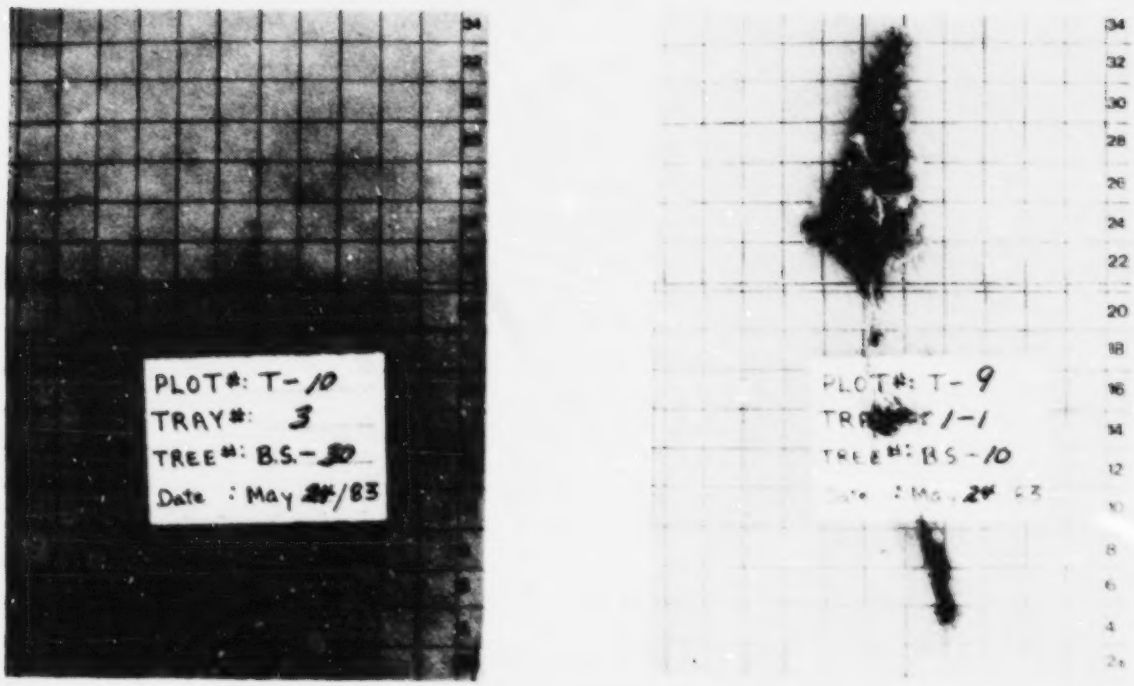


Figure 10: Graph of Cu and Ni in seedling root tissue versus root growth for black spruce.

jack pine seedlings

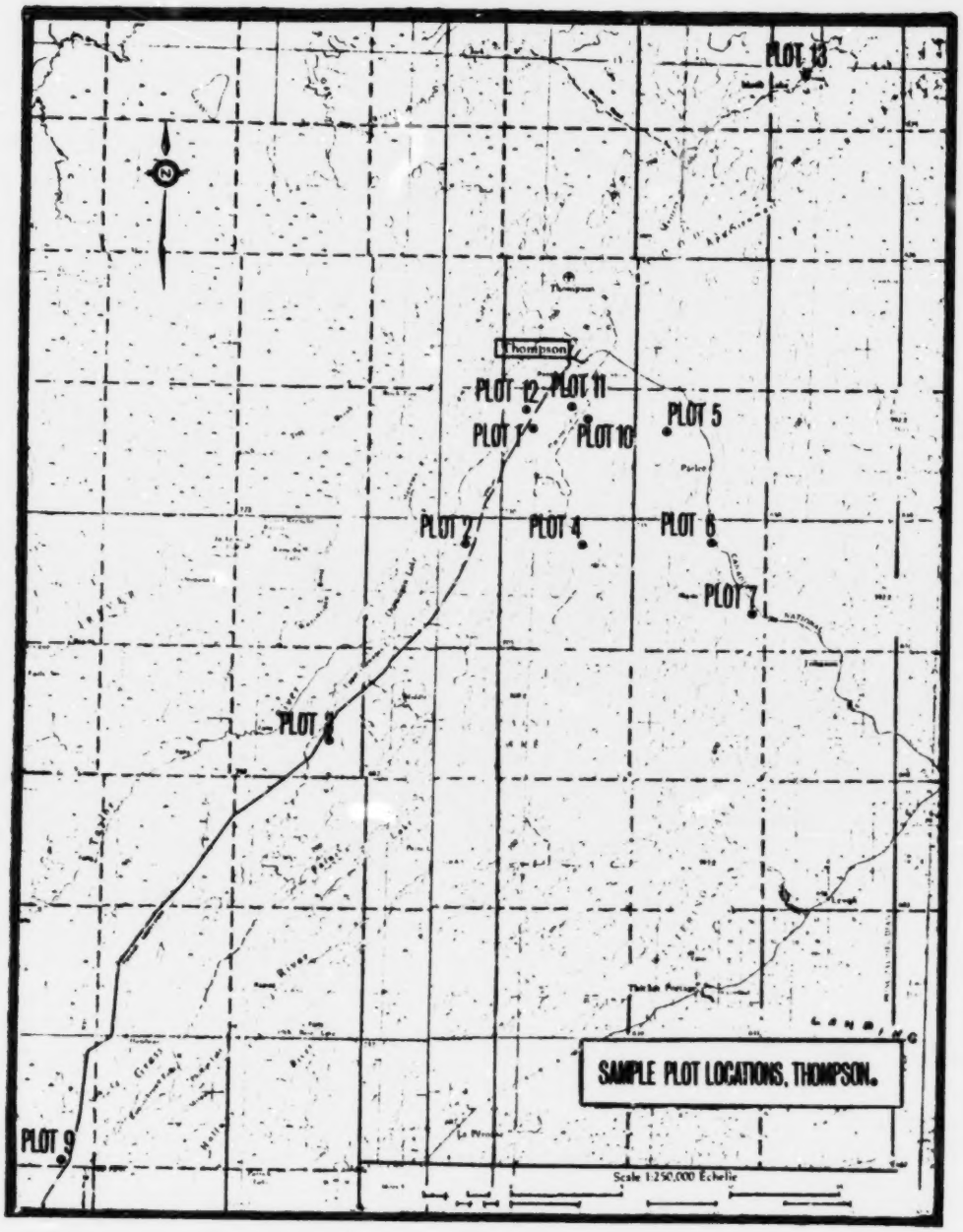


black spruce seedlings

Figure 11: Photographic illustration of jack pine and black spruce growth suppression.

APPENDICES

Appendix 1: Map of Thompson Federal/Provincial site locations



Appendix 2: Regression correlation coefficients (r^2) for metal levels in LFH versus distance from the Inco smelter

Jack Pine						Black Spruce					
Pb	Zn	Fe	Cu	Ni	Cd	Pb	Zn	Fe	Cu	Ni	Cd
NS	0.50	0.59	0.95	0.91	0.80	0.60	NS	0.79	0.92	0.85	0.55
	xxx	xxx	xxx	xxx	xxx	xxx		xxx	xxx	xxx	xxx

xxx r^2 significant at 1 percentile ($p = 0.01$)
NS r^2 not significant

Appendix 3: Regression correlation coefficents (r^2) for metal levels in seedling tissue versus metal levels in LFH.

Metals Levels in LFH	Metal Levels in Seedling Tissue											
	Pb		Zn		Fe		Cu		Ni		Cd	
	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots
Pb	0.50 xxx (NS)	NS (NS)	-	-	-	-	-	-	-	-	-	-
Zn			NS (NS)	NS (NS)	-	-	-	-	-	-	-	-
Fe	-	-	-	-	0.68 xxx (0.43) (xxx)	0.43 xxx (NS)	-	-	-	-	-	-
Cu	-	-	-	-	-	-	0.90 xxx (0.93) (xxx)	NS (NS)	-	-	-	-
Ni	-	-	-	-	-	-	-	-	0.92 xxx (0.92) (xxx)	0.86 xxx (0.75) (xxx)	-	-
Cd	-	-	-	-	-	-	-	-	-	-	NS (NS)	NS (0.55) (xxx)

xxx r^2 significant at 1 percentile ($p = 0.01$)
NS r^2 not significant
( ) black spruce coefficients

Appendix 4: Regression correlation coefficients (r^2) for metal levels in seedling tissue versus distance from the Inco smelter and seedling growth and biomass.

Seedling Measurements	Metal Levels in Seedling Tissue												Distance
	Pb		Zn		Fe		Cu		Ni		Cd		
	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	
Mean Oven Dry Shoot Mass	0.40[1] xx (0.26)[2] (x)	0.44 xxx (0.43) (xxx)	 NS (0.64) (xxx)	0.60 xxx (NS)	0.61 xxx (NS)	 NS (NS)	0.75 xxx (0.46) (xxx)	 NS (0.67) (xxx)	0.65 xxx (0.55) (xxx)	0.59 xxx (0.54) (xxx)	 NS (0.49) (xxx)	 NS (NS)	0.57 xxx (0.30) (x)
Mean Oven Dry Root Mass	0.32 xx (NS)	0.46 xxx (0.62) (xxx)	 NS (0.37) (xx)	0.57 xxx (NS)	0.68 xxx (NS)	0.29 x (0.25) (x)	0.61 xxx (0.64) (xxx)	 NS (0.71) (xxx)	0.57 xxx (0.49) (xxx)	0.42 xx (0.48) (xxx)	 NS (0.71) (xxx)	0.25 x (NS)	0.41 xx (0.46) (xxx)
Mean Shoot Length	0.46 xxx (0.26) (x)	0.51 xxx (0.69) (xxx)	 NS (0.43) (xxx)	0.55 xxx (NS)	0.62 xxx (NS)	0.30 x (NS)	0.59 xxx (0.66) (xxx)	 NS (0.76) (xxx)	0.61 xxx (0.59) (xxx)	0.33 x (0.53) (xxx)	 NS (0.63) (xxx)	 NS (NS)	0.42 xx (0.43) (xxx)
Mean Root Length	0.6 xxx (0.41) (xx)	0.88 xxx (0.83) (xxx)	 NS (0.57) (xxx)	0.74 xxx (NS)	0.88 xxx (NS)	0.40 xx (NS)	0.86 xxx (0.75) (xxx)	 NS (0.75) (xxx)	0.76 xxx (0.68) (xxx)	0.57 xxx (0.64) (xxx)	 NS (0.71) (xxx)	 NS (NS)	0.66 xxx (0.49) (xxx)
Distance	0.49 xxx (NS)	0.39 xx (0.48) (xxx)	 NS (NS)	0.75 xxx (0.29) (x)	0.54 xxx (0.28) (x)	 NS (NS)	0.82 xxx (0.82) (xxx)	 NS (NS)	0.81 xxx (0.66) (xxx)	0.79 xxx (0.51) (xxx)	 NS (0.58) (xxx)	 NS (0.68) (xxx)	

x r^2 significant at 5 percentile ($p = 0.05$)
xx r^2 significant at 2.5 percentile ($p = 0.025$)
xxx r^2 significant at 1 percentile ($p = 0.01$)
NS r^2 not significant

1. jack pine coefficients
2. black spruce coefficients